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SPALLATION BY DUCTILE VOID GROWTH*

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ABSTRACT

A mathematical model of ductile void growth under the application of a mean tensile stress is applied to the problem of spallation in solids. Calculation of plate-impact spallation in copper (peak compressive stress ~29 kbar) shows good agreement with the dynamically measured spall signal. A second calculation, using identical material parameters, of explosively produced spallation in copper (peak compressive stress ~250 kbar) does very well in reproducing experimentally observed multiple spall thicknesses as observed by dynamic x-radiographic techniques. This theoretical model thus appears applicable to a wide range of dynamic uniaxial-strain loading conditions, bridging a gap that has been thought to exist for some time.

INTRODUCTION

For every spallation experiment that is conducted, an ad hoc model can be developed to reproduce damage levels (in the form of residual porosity), spall location, growth rates, and so on. What is presently lacking is a single model of ductile fracture capable of reproducing the experimental results obtained under widely varying conditions. For example, in the work of Breed, Mader, and Venable¹ on explosively produced spallation of copper, a computational model of fracture was developed to correlate spall strength with spall thickness. This model has been useful in reproducing the observed spall layers in explosive events, but is not applicable to low-pressure plate-impact experiments. Likewise, models developed for plate-impact situations seem to be inadequate in the high-pressure regime.² These models were developed to represent accurately the onset of fracture in engineering design and no attempt was made to see how they worked under the very extreme conditions of explosive loading at 200-300 kbar.

In the present work, the results of a microscopic model for ductile hole growth are presented which relate the material porosity (an internal state variable) to its initial value, the time history of the tensile pressure (or mean stress), and a single scalar parameter representing the rate-dependent plastic flow properties of the solid material surrounding the voids. This introduces a minimum number of adjustable parameters--also, the ones that are used have the possibility of being determined experimentally.

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VOID-GROWTH RELATIONS FOR DUCTILE MATERIALS

Carroll and Holt³ describe a very useful model of ductile void collapse that lends itself directly to a theory of void growth under tensile loading conditions--the only difference is that the pressure, p , is negative in the void-growth case and the porosity increases. In addition to the obviously trivial replacement of p with $-p$ in Carroll and Holt's model, a rate-dependent plastic flow term is added that was not in the original development.⁴

Ductile void growth is expressed in terms of the distention ratio $\alpha \equiv V/V_s$, where V is the average specific volume of a region containing voids and V_s is the specific volume of the solid material surrounding the voids. The void-growth rate due to an average mean tensile stress p is given by

$$(\rho a_0^2/3)(\alpha_0 - 1)^{-2/3} Q(\ddot{\alpha}, \dot{\alpha}, \alpha) = \alpha p + (2Y/3) \ln \frac{\alpha}{\alpha - 1} + \eta(\alpha_0 - 1)^{-2/3} (\alpha - 1)^{-1/3} \dot{\alpha} \quad (1)$$

where

$$Q(\ddot{\alpha}, \dot{\alpha}, \alpha) \equiv -\ddot{\alpha}[(\alpha - 1)^{-1/3} - \alpha^{-1/3}] + \frac{1}{6} \dot{\alpha}^2 [(\alpha - 1)^{-4/3} - \alpha^{-4/3}] \quad (2)$$

In Eq. (1) a_0 is the average initial void radius giving an initial distention ratio α_0 , Y is the yield strength of the solid, and η is the "viscosity" of the solid (i.e., the proportionality constant between shear stress and plastic strain rate).

PLATE-IMPACT AND EXPLOSIVELY GENERATED SPALL IN COPPER

As an application of the foregoing theory, two quite different spallation experiments on copper are calculated by the finite-difference method. The first is a plate-impact experiment⁵ in which a 0.6-mm-thick copper plate strikes a 1.6-mm copper target backed by a relatively thick plate of PMMA (polymethylmethacrylate) in which a man-ganin pressure gauge is embedded approximately 0.5 mm from the copper (target)/PMMA interface. The impact velocity of 0.016 cm/ μ s produces a 29-kbar peak stress in the copper. Application of the dynamic hole growth analysis to the problem of time-dependent spallation in copper is shown in Fig. 1. The peak shock amplitudes are in some disagreement, but the spall signals ($t > 0.8 \mu$ s) show good agreement.

The initial distention $\alpha_0 = 1.0003$ is taken to be the measured porosity in the recovered sample at locations far from the spall plane: the actual porosity prior to shock loading was not reported.⁵ The average initial pore radius is determined to be 1.9×10^{-4} cm

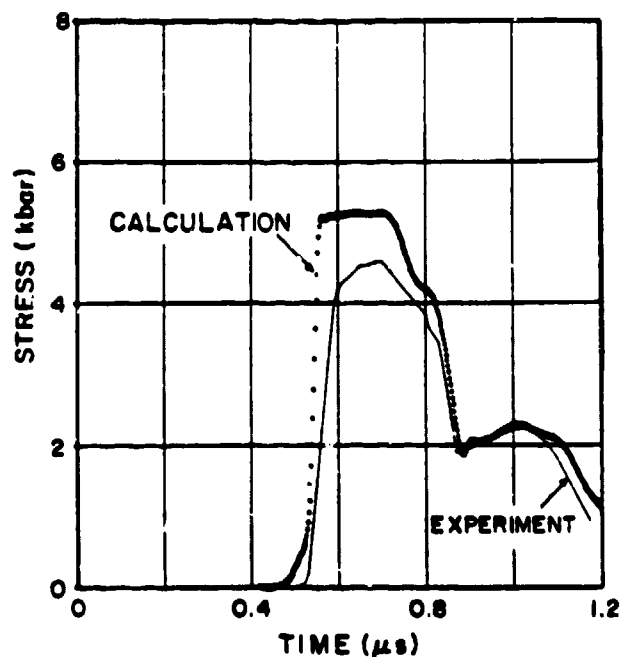


Fig. 1. Calculated spall signal in copper compared with experimental measurement.

from α_0 and the measured void number density (10^7 cm^{-3}).⁵ Other void growth parameters used here are $Y = 2.6 \text{ kbar}$ and $\eta = 10 \text{ poise}$.

To demonstrate the generality of the foregoing model of dynamic ductile fracture of copper, as determined by a single plate-impact experiment, a finite-difference calculation is made of explosively produced spall fracture in copper. A 12.7-mm-thick piece of Composition B in contact with a 25-mm-thick copper plate produces two distinct spall planes--the first (closest to the free surface) plane is approximately 2 mm thick and the second plane is approximately 3 mm thick.⁶ A spallation calculation is

made with the same pore-growth model used for the plate-impact experiment: the material parameters remain exactly the same, only the loading conditions are changed. The results of this calculation are shown in Fig. 2 ($t = 6.0 \mu\text{s}$) where a region about 2 mm thick is continually fractured, but the major discontinuities in particle velocity define two spall planes, one 2 mm thick, closest to the free surface, and the second 3 mm thick as observed experimentally.

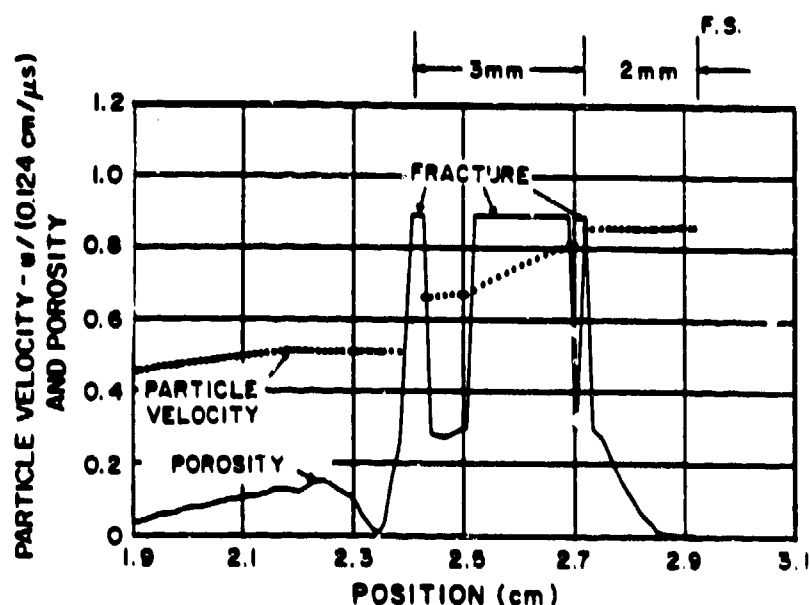


Fig. 2. Final calculated fracture and porosity distribution for Los Alamos PHERMEX shot 500. The region between the two visible spall planes (i.e., those with particle velocity discontinuities) continues to break up after spall plane formation. The free surface (F.S.) is located at the 2.92-cm position.

SUMMARY

A ductile hole-growth model is applied to the problem of spall fracture of copper for plate-impact and explosive loading conditions. Previous models have been found to work well in the incipient stages of ductile fracture, while others seem to be more applicable to complete separation. The description presented here thus tends to bridge the gap between the low-damage and complete separation regimes of spall fracture.

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